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Groundwater depletion and contamination: Spatial distribution of groundwater resources sustainability in China

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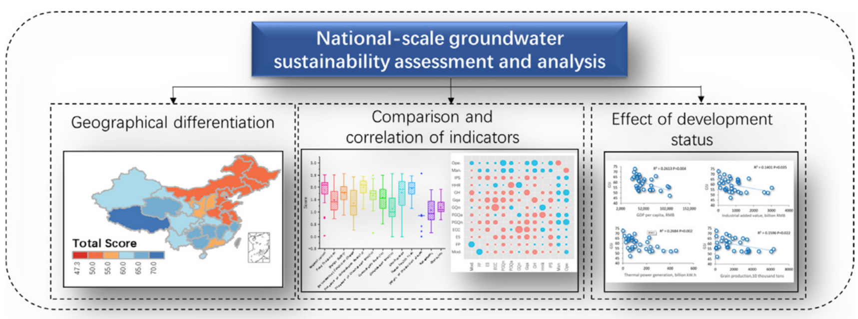
HIGHLIGHTS

- Developed an indicator system for sustainability assessment of groundwater resources
- Assessed the spatial distribution of groundwater resource sustainability in China
- Analyzed the interrelationship of different sustainability indicators
- Evaluated the effect of development status on groundwater resource

GRAPHICAL ABSTRACT



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ABSTRACT

China is facing a groundwater depletion and deterioration crisis, culminating from long-term over-exploitation and groundwater contamination. Aggravating factors include population growth, unprecedented urbanization and climate change. Sustainable groundwater management is called for, however, a valid means for a national-scale assessment of groundwater resource sustainability does not currently exist. Here we present a drivers-pressures-states-impact-response (DPSIR) assessment framework. Based on this framework, groundwater sustainability indices for mainland China's 31 provinces and municipalities were derived, with an average score of 59.5 out of 100, ranging from 47.3 for Tianjin to 72.9 for Tibet. We found that due to fewer Drivers and better States, groundwater resources in southern China are far more sustainable than those in the northern and eastern areas. An appraisal of subcategories shed light on the importance of affording attention to externalities such as societal, economic and environmental factors, which are interrelated as complex systems. Based on the assessment findings, implications for policy and decision-making suggestions for sustainable management of China's groundwater resources are put forward.

1. Introduction

Groundwater provides essential water for humans and human dependent ecosystems. In China, groundwater provides drinking water

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for >400 cities. In northern China, two thirds of drinking water, half of industrial water, and a third of irrigation water is supplied from groundwater sources (MEP, 2011). In rural areas, domestic potable water is mainly provided by private wells (Jia et al., 2018). It was reported in 2011 that there were an estimated 53.8 million groundwater extraction wells in China. Only 23 years earlier, that number was just 4 million (Chen and Ma, 2017). Evidently, groundwater is an increasingly important resource for the population of China.

Due to unsustainable anthropogenic activities, severe groundwater depletion has occurred in China, particularly in the mainly arid and semi-arid areas of the North China Plain and across northwestern China, thus threatening food production, industrial domestic water supplies and the sustainable development (Jin and Feng, 2013; Yang et al., 2006). In addition, groundwater overexploitation has caused severe land subsidence, sea water intrusion and ecological damage in eastern China (Han et al., 2011; Ye et al., 2015). Between 1959 and 2013, for example, the eastern city of Tianjin subsided by an estimated 3.44 m (Ye et al., 2015), and hundreds of earth fissures have been observed in the Hebei Plain and Fenwei Basin (Lv et al., 2014; Pen et al., 2007).

Moreover, groundwater pollution levels are reported to be severe. Over 60% of the groundwater in China is either poor or very poor quality (class IV or V), according to the Ministry of Land and Resource's national groundwater monitoring network (Bagordo et al., 2016; Hou et al., 2018a). A nationwide water quality survey revealed at least one harmful organic compound in 48% of samples tested (Guo and Wang, 2011). For instance, in the Datong Basin, arsenic concentrations can be as high as 452 μg/L (Zhang et al., 2013). Such contaminants derive from both natural pedogenic sources and anthropogenic activities (Gu et al., 2013; Kang et al., 2017), posing a public health risk (Jin et al., 2019; O'Connor et al., 2019a). An estimated 19.6 million people are at risk of the harmful effects of arsenic in their drinking water supplies, and high total dissolved solids (TDS), Fe, Mn, As and F are also frequently observed in monitoring wells (Jia et al., 2018) as well as other emerging contaminants (O'Connor et al., 2019b). Among anthropogenic activities, intensive agricultural and industrial activities are identified as key culprits for deteriorating groundwater quality. Fertilizer and manure used for food production are sources of nitrogen in groundwater (Gu et al., 2013). Contaminated groundwater also threatens food safety when pollutants enter the food chain through crop irrigation.

Some researchers have suggested that groundwater systems are part of the coupled human-nature system. Consequently, to support the establishment of a comprehensive GSA framework, existing theories of the interactions between groundwater and human-nature system need to be considered. Undoubtedly, groundwater is an essential resource for humans, not only for domestic water supplies but also for industry, and agricultural food production. For natural systems, groundwater delivers water to surface water systems and plants, and maintains ground stability (Zhang et al., 2015). Intensive industrial and agricultural production has led to the overexploitation of groundwater. Falling water tables are the most direct issue, which leads to increased difficulty/cost in groundwater extraction (Famiglietti, 2014), as well as changes in base flow to rivers, lakes, springs, wetlands and surface plants, and ecosystem degradation (Wada et al., 2010). Moreover, land subsidence and sea water intrusion can occur, thus roads, railways and building infrastructure may be damaged (Dong et al., 2014; Shi and Jiao, 2014). In addition, groundwater depletion can exacerbate the migration of pollutants (Aeschbachhertig and Gleeson, 2012).

The sustainability of groundwater resources depends on complex feedback loops between human and natural systems (Hou et al., 2012). In a positive feedback loop, additional groundwater depletion and deterioration will affect human development, consequently there is less resources devoted to groundwater protection, which worsens the situation and leads to more groundwater deterioration. In a negative feedback loop, when additional groundwater depletion and deterioration occurs, groundwater quality and quantity will be monitored, water-saving technologies for agriculture and industry will be promoted, wastewater treatment will be improved, polluted groundwater remediation will be implemented and policies for groundwater management will be modified (Hou and Li, 2017) (Song et al., 2019).

Depletion and deterioration of groundwater resources by human activities generates multiple impacts to human-nature systems and negative consequences for sustainable development. Therefore, sustainable groundwater management is called for. For this, a comprehensive assessment of the groundwater sustainability situation is essential (Megdal, 2018) in order to pinpoint and address the issue effectively. To appraise groundwater sustainability, there are a number of groundwater sustainability assessment (GSA) models/tools, covering aspects such as groundwater quantity, quality, safe utilization and venerability (Cao et al., 2013a; Cheng et al., 2010; Zhan et al., 2017). However, there is no comprehensive national-scale sustainability assessment framework that has been applied to China. One candidate model is the "Groundwater resource sustainability indicators", first proposed by the United Nations Educational, Scientific and Cultural Organization (UNESCO), which includes ten indicators based on the diver-pressure-state-impact-response (DPSIR) theory (Vrba et al., 2007). But while the indicators are effective for assessing groundwater quality and quantity, they do not explicitly address the three pillars of sustainability (society, economy, environment).

Frameworks based on the DPSIR theory or the three dimensions of sustainability have been applied at a local level (e.g. provincial) in China (Bagordo et al., 2016; Chen et al., 2015; Pandey et al., 2010). However, they are not implementable on a national-scale. In these GSA frameworks, several nationally important aspects of groundwater sustainability are not considered, such as the impact of groundwater depletion to production systems. Moreover, many of the qualitative indicators used are based on local assumptions, making comparison between regions difficult. Consequently, a comprehensive and national-scale GSA framework is needed.

The key objectives of the present study were as follows: (1) to develop the first comprehensive GSA framework for a national-scale assessment of China including the dimensions of society, economy and environment; (2) to undertake the first national assessment of mainland China, including calculation of groundwater sustainability scores for the different provinces and municipalities; and (3) to put forward implications for decision-making and policy implementation based on the assessment.

2. Method and data

2.1. Proposed groundwater sustainability assessment framework based on DPSIR theory

The DPSIR causal framework was first developed by the European Environment Agency as an extension of the Pressure-State-Response (PSR) model developed by the Organization for Economic Cooperation and Development (OECD). It provides researchers a way to analyze interactions between human activities and environmental systems (Khajuria and Ravindranath, 2012; Lin et al., 2013; Pirrone et al., 2005). The five components involved in DPSIR are interconnected with each other. Drivers are the forces of economic and societal development, as well as population and environmental change. Pressures arise when drivers occur in a system. The state of a system or environment is then changed, which causes an impact to services provided. In response, policies will be established and actions taken to help mitigation or adaption to the changed system (Pandey et al., 2010; Righi, 1999).

In this study, DPSIR indicators reveal not only the situation of groundwater sustainability in China, but also the interaction between groundwater and human-nature systems. The indicator system is divided into the five DPSIR categories, which we further divided into 14 subcategories (Table 1). The framework presented is established mainly

Table 1
Indicators in groundwater sustainability assessment system.

Category	Subcategory	Indicator	Analysis[1]	Other GSA studies also using the indicator
Drivers	Modernization	Population density	Quan	(Bagordo et al., 2016)
		GDP per capita	Quan	(Jiang et al., 2015)
		Rate of urbanization	Quan	(Hazarika and Nitivattananon, 2016; Pandey et al., 2010)
		Percentage of impervious area	Quan	(Pandey et al., 2010)
	Food Production	Grain production per capita	Quan	(Borji et al., 2018)
		Vegetable production per capita	Quan	(Borji et al., 2018)
		Meat production per capita	Quan	(Bagordo et al., 2016)
	Energy Supply	Fossil fuel production	Quan	
		The portion of thermal power generation	Quan	
		Biofuel	Quan	
	Environmental Condition Change	Precipitation	Quan	(Borji et al., 2018)
		Surface water quality	Quan	
Pressures	Pressure to Groundwater Quantity	Total water consumption	Quan	(Borji et al., 2018)
		Groundwater extraction per unit area	Quan	(Vrba et al., 2007)
		Rate of groundwater exploitation	Quan	(Jiang et al., 2015)
		Water consumption per GDP	Quan	
	Pressure to Groundwater Quality	The amount of wastewater	Quan	(Borji et al., 2018)
		The amount of fertilizer and pesticide usage	Quan	
		Poor water quality of anthropogenic origin	Semi	
State	Groundwater Quantity	Groundwater resources per area	Quan	(Jiang et al., 2015)
		Groundwater level	Quan	(Pandey et al., 2010)
	Groundwater Quality	Groundwater quality	Quan	(Vrba et al., 2007)
		Contamination of nitrogen	Semi	(Bagordo et al., 2016; Mattas et al., 2014)
	Geo-hazards	Land subsidence	Semi	(Pandey et al., 2010)
		Seawater intrusion	Semi	
Impact	Human Health Risk	Drinking water safety	Quan	(Pandey et al., 2010)
		Food safety caused by polluted irrigation water	Quan	
		Vapor intrusion	Quan	
	Impact to Production System	Industry production	Quan	
		Food production	Quan	
		Energy production	Quan	
Responses	Management	Regulation of groundwater resources	Semi	(Pandey et al., 2011)
		Enforcement	Quan	
		Capacity building	Quan	(Pandey et al., 2011)
	Operation	Groundwater monitoring	Quan	(Pandey et al., 2010)
		Wastewater treatment	Quan	(Bagordo et al., 2016)
		Rate of water-saving irrigation	Quan	
		Water intervention	Quan	(Hazarika and Nitivattananon, 2016)
		Prevention and control of groundwater pollution	Quan	

[1] : Quan = Quantitative; Semi = Semi-quantitative.

on the existing theory on the interactions between groundwater and coupled human-nature systems, as well as previous research on GSA.

2.1.1. Drivers

The unprecedented modernization characterized by population explosion, urbanization and economic development is the main contributor to environmental pollution and resource depletion (Hazarika and Nitivattananon, 2016). To meet the demand of modernization, intensive energy production and food production is often carried out. Recently, researchers have focused on the close relationships in the energy-water-food security nexus (Bazilian et al., 2011; Endo et al., 2015). Apart from anthropic drivers, changing natural factors are also a driver for groundwater unsustainability (Scanlon et al., 2012; Trenberth, 2011). To address these, the Drivers are divided into the four subcategories of modernization, food production, energy supply and environmental condition change.

Modernization comprises of four specific indicators: population density, GDP per capita, rate of urbanization and percentage of impervious area. Population explosion, described by population density, not only means the increasing number of people but also the demands of this rising population, food, energy, water, space and so on, which exert pressures to groundwater system (Jago-On et al., 2009). China has experienced unprecedented economic development, which brings pressure to both groundwater quality and quantity, due to its exploitation for agriculture and industry (Jackson, 2006). Thus, GDP per capita was selected. High population density and improved lifestyle in urban areas has increased domestic water consumption, and land use change and new infrastructure has reduced the permeability of large amounts of land area reducing the recharge of groundwater (Howard, 2015). Consequently, indicators for rate of urbanization and percentage of impervious area were incorporated as two drivers.

Food production involves three indicators: grain production per capita, vegetable production per capita and meat production per capita. China, with 7% of the world's arable land, provides food for 22% of the global population (CSY, 2017). In northern China, especially the North China Plain, intensive agriculture practices are performed. The majority of irrigation water there is supplied by groundwater since surface water sources are scarce (Changming et al., 2001). Increasing livelihoods in China now requires the agriculture sector to not only provide enough grain, but also nutritious and higher valued foods (Huang, 2010; Wang and Qi, 2013), thus requiring greater irrigation water consumption, fertilizer/pesticides use, and increased livestock excrement (Gu et al., 2013; Shi et al., 2009; Siebert et al., 2010), which exert pressure on both quantity and quality of groundwater.

Energy supply includes three indicators: fossil fuel production, the proportion of thermal power generation, and the proportion of biofuel. Fossil fuel production has a significant impact on groundwater, due to instances such as petroleum hydrocarbon leakage in the process of exploitation and transport (Lesage et al., 1997). Coal mining is also identified as a threat to aquifers, due to the lowering of groundwater levels by dewatering for coal excavation (Wang et al., 2010). Therefore, the amount of petroleum and coal production is included to indicate the influence of primary energy production on groundwater resources. As for secondary energy, the portion of thermal power generation was selected due to its massive coal and water demands (Wei et al., 2014). Biofuel, a kind of clean energy, was also selected as an indicator. This is

because considerable water amounts are required to grow the crops used for biofuels, as well the use of fertilizer and pesticides (Dominguezfaus et al., 2009).

Environmental condition change incorporates two indicators: surface water quality and precipitation. With the degradation of surface water quality and quantity, groundwater is increasingly relied upon, which exert stress to groundwater resources (Wang and Jiao, 2012). Furthermore, pollutants in contaminated surface waters can transfer to groundwater. The amount of precipitation will strongly influence the distribution of shallow groundwater resources (Scanlon et al., 2012). Thus, surface water quality and precipitation are selected as two natural driving forces.

2.1.2. Pressures

The pressures generated by drivers affect groundwater system in two ways: (1) decreasing groundwater quantity; (2) deteriorating groundwater quality (Jago-On et al., 2009). Accordingly, pressures are divided to two subcategories: pressures to groundwater quantity and pressures to groundwater quality.

Pressures to groundwater quantity includes 4 indicators: total water consumption, groundwater extraction per unit area, rate of groundwater exploitation and water consumption per GDP (Chen et al., 2015; Gao et al., 2007; Liu et al., 2005; Sun et al., 2016). Total groundwater consumption indicates the overall consumption level of a province. Groundwater extraction per unit area indicates the reliance on groundwater. Rate of groundwater exploitation, the ratio of groundwater extraction to groundwater resources reflects the intensity of groundwater extraction. The former three indicators give a direct understanding about the state of groundwater usage, whereas the latter details water usage efficiency.

Pressures to groundwater quality is endangered by human activity, but natural background contamination can also cause harm in certain areas (Bagordo et al., 2016; Jago-On et al., 2009). Thus, indicators for the amount of wastewater, the amount of fertilizer and pesticide usage and poor water quality of geogenic origin are selected. The amount of wastewater includes the discharge from industrial production and domestic activity, which causes pressure to groundwater to mainly in two ways: 1) leakage from contaminated wastewater pipes; 2) recharge of surface water by contaminated wastewater (Li et al., 2015b; McCance et al., 2018; Zeng et al., 2016). Agriculture is a vital stress producer for groundwater, not only for the size of its water consumption compared with domestic and industry, but also for the impact of pesticides and fertilizer usage on groundwater quality (Li et al., 2015b; Malaguerra et al., 2012; Shi et al., 2009). For example, serious nitrogen pollution in groundwater caused by fertilizer utilization has been reported in many provinces in China (Gu et al., 2013). Closely related to geology, geogenically contaminated groundwater is commonly found in China (Jia et al., 2018; Ren and Jiao, 1988). Therefore, the poor water quality of geogenic origin is included.

2.1.3. State

Under the influence of drivers and pressures, the state of the groundwater system will change (Jago-On et al., 2009), in both the dimensions of quantity and quality. Therefore, subcategories of quantity and quality are used as indicators of this. The subcategory of groundwater quantity consists of exploitable groundwater resources and groundwater level (Chen et al., 2015; Pandey et al., 2010), which indicates groundwater abundance in different provinces. Groundwater quality has a close relationship with human health because it is a source of irrigation water and drinking water (Bhattacharya et al., 2010; Wu and Sun, 2015). This indicator is based on the Standards of Groundwater Quality in China, being defined as the ratio of groundwater better than Class III. Nitrogen contamination is a particular threat to groundwater in China (Gu et al., 2013), and is also included as an indicator in this subcategory.

2.1.4. Impact

The supply of groundwater resources to other system can be divided into three categories, (i) supplying water to human systems, (ii) supplying water to ecosystems and (iii) supporting land structures (Zhang et al., 2008). Therefore, the depletion or deterioration of groundwater hinders the provision of groundwater services to these systems. Hence, the impact category includes three subcategories: geo-hazard, human health risk and impact to production systems.

Groundwater overexploitation can bring about severe geo-hazards, such as land subsidence, earth fissures and sea water intrusion (Shi and Jiao, 2014; Ye et al., 2015). Land subsidence now seriously influences the sustainability of regional economy and society by damaging infrastructure (Jia et al., 2017). Seawater intrusion caused by overexploitation of groundwater will bring about soil and groundwater salinization, thus resulting in economic and social loss (Shi and Jiao, 2014).

Human health risk includes drinking water safety, food safety and vapor intrusion. >400 major cities in China use groundwater as their drinking water source (MEP, 2011). Thus, as groundwater quality worsens, exposure to greater health risk will increase. Moreover, when irrigation water comes from contaminated groundwater, pollutants, such as arsenic or cadmium can be taken up by crops for consumption by human (Bhattacharya et al., 2010; Garnier et al., 2010). Vapor intrusion by volatile pollutants in groundwater is also included because of the severe risk of inhaling harmful pollutants (Gao and Wang, 2011; Little et al., 1992).

Impact to production system consists of three indicators: industry production, food production and energy production. Water is a fundamental factor in production activities, and due to over-exploitation, impacts can arise (Foster et al., 2004)., the indicators in this subcategory are supposed to scale the impact caused by inadequate water supply.

2.1.5. Responses

Responses contains the measures taken by humans to improve groundwater sustainability, of which management is an essential component. Additionally, to improve both the quality and quantity of groundwater, specific operations are called for. Consequently, management and operation are subcategories used to assess responses. The establishment of a separated regulation of groundwater management indicates groundwater management of a province (Howard, 2015). Enforcement is also included, because it determines whether an established policy is effective. Capacity building is used to evaluate improved groundwater management. Five indicators are used for the operation which are groundwater monitoring, wastewater treatment, the rate of water-saving irrigation and water intervention. Groundwater monitoring reveals the quality and quantity of groundwater (Pandey et al., 2011). Industrial and domestic wastewater treatments reduce pollution levels entering into groundwater. Implementation of water-saving irrigation will decrease water pumped from groundwater and alleviate groundwater depletion. And water intervention provides assurance that groundwater is not contaminated with arsenic and fluorine (Tong and Xia, 2018). Prevention and control of groundwater pollution indicates the efforts made to improve groundwater quality.

2.2. Data sources

Data used in the model for China was extracted from numerous sources. Data on GDP, the rate of urbanization, grain production, total water consumption, groundwater consumption was extracted from the China Statistical Yearbook (2015) (CSY, 2016d). Vegetable production, meet production, the consumption of fertilizer and pesticides, irrigation area, water saving irrigation area was extracted from the China Rural Statistical Yearbook (2015) (CSY, 2016c). Energy data such as thermal power generation, crude oil production, raw coal production, total power generation was extracted from the China Energy Statistics Yearbook (2015) (CSY, 2016a). Data on population density was extracted from the China Population and Employment Statistics Yearbook

(2016) (CSY, 2016b). Relevant data is also made available by the Chinese government via announcements, plans, reports or bulletins. For example, pertinent data on 'Enforcement' was extracted from the 'Special Plan for Water Pollution Prevention and Control in Key River Basins' (2015), which details how effectively provinces enforce environmental policies.

Data on precipitation and surface water quality was collected from the Environmental Conditions Report and Water Resource Bulletin published provincially. The total value of groundwater rescores was gathered from the China Statistical Yearbook (2015) (CSY, 2016d). Data for groundwater levels were extracted from the China Geological Environment Monitoring Groundwater Level Yearbook (2014) (CIGEM, 2015). Groundwater quality data for 16 provinces came from the Groundwater Monthly Report (2016) (MWR, 2016). For other provinces, we used average data published in China's Environmental Conditions Report (MEP, 2016). Sea water intrusion is recorded in China's Marine Disaster Bulletin (2015) (SOA, 2016). Datasets for drinking water safety and water intervention were collected from the China Health and Family Planning Statistics Yearbook (2015) (NHC, 2016). Data for wastewater treatment was obtained from China Urban Construction Statistical Yearbook (2016) (MOHURD, 2016). The data for groundwater monitoring points in each province was collected from the GeoCloud website (http://geocloud.cgs.gov.cn/#/portal/home). For poor water quality of geogenic origin, nitrogen contamination and land subsidence, we extracted data on concentration, area affected, and point of pollutant density from published articles. The data sources for each indicator are listed in Table S1.

2.3. Weighting, normalizing, and sensitivity analysis

In this study, indicators were assumed to have the same value, and therefore given an equal weighting of 1. For quantitative indicators, data was directly inputted. For semi-quantitative indicators, a scoring system of 1 to 5 was used based on literature benchmarking. Data for different indicators have different units and therefore cannot be combined in a comprehensive index. Therefore, we used Min-max Normalization to weigh data from 0 to 1, with values closer to 1 being more desirable. The data processing steps in detail are as follows.

For m provinces whose groundwater sustainability will be measured (i = 1,2, …,m). and n evaluated parameters (j = 1,2, …,n), matrix X can be constructed as:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \ddots & \vdots \\ \vdots & \vdots & & \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{1}$$

To normalize positive indicators, the function is as follows (Bo et al., 2010; Li et al., 2011):

$$x\prime_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}} \tag{2}$$

And for negative indicators, the function is as follows:

$$x\prime_{ij} = \frac{x_{max} - x_{ij}}{x_{max} - x_{min}} \tag{3}$$

Then, the comprehensive index of groundwater sustainability for different provinces can be calculated as:

$$GSI_i = \sum_j (w_i x\prime_{ij}) \times \left(\frac{100}{39}\right) = \sum_j x'_{ij}\left(\frac{100}{39}\right) \tag{4}$$

The score of the different DPSIR categories and subcategories can be calculated as the sum of the indicators. The score of a certain category or subcategories for X_i province can be calculated as:

$$X_i = \sum_m (x\prime_{ij}) \times \left(\frac{100}{39}\right), \tag{5}$$

where m is the number of indicators included in the category.

To aid comparison among the DPSIR categories, the scores were normalized as follows:

$$NX = \frac{X}{m} \tag{6}$$

where NX is the normalized score and m is the number of indicators contained within each category.

3. Results and discussion

3.1. Overall sustainability of groundwater resources in China

The assessment system for groundwater sustainability scored each of the 31 provinces and municipalities of mainland China, which varied from 47.3 to 72.9, with an average score of 59.5 and median of 58.9. Tibet was the highest scoring province, while the lowest was Tianjin. Moreover, the scores for different categories among the provinces are shown in Table 2, which were calculated using Eq. (5). To compare the general performance of the five categories, we normalized the scores as shown in Fig. 1. Pressures' scored the most desirably among the five parts, with a score of 1.9, while 'Responses' performed the worst with score of 1.1. China is a developing country, which may help explain the unbalanced that has been identified in the drivers and pressures (Zhan and Wang, 2018). The poor performance of some states are an evidence to groundwater unsustainability in China. In

Table 2
Groundwater sustainability in different provinces in China.

Province	Drivers	Pressures	State	Impact	Responses	Total Score
Tibet	25.4	16.5	6.9	18.8	5.3	72.9
Guizhou	23.8	16.7	7.1	14.3	7.9	69.8
Guangxi	23.1	13.5	8.6	11.7	11.1	68
Qinghai	23.2	16.4	7.3	15.2	5.4	67.5
Zhejiang	22.9	13.7	8.2	9.4	11.8	66
Jiangxi	23.6	13.9	7.9	13.4	7.2	65.9
Hunan	22.9	13.1	7.3	11.9	10.1	65.3
Yunnan	24.5	14.8	6.7	11.1	7.8	64.9
Sichuan	22.4	14.3	5.5	13.9	8.1	64.3
Gansu	22.6	14.6	5	14	7.2	63.4
Chongqing	20.9	16.3	4.3	14.3	7.2	63
Fujian	23.2	12.7	6.8	10.6	9.5	62.8
Xinjiang	19.8	8.6	4.9	14.9	13.3	61.5
Hubei	21.7	13.3	6.7	12.4	7.4	61.4
Hainan	21.5	14.9	6.8	12.9	5.1	61.2
Shaanxi	19.8	13.8	4.3	11.6	9.4	58.9
Ningxia	19.4	13.6	2.4	14.3	7.3	57
Guangdong	22.5	8.3	7.2	9.2	9.8	56.9
Shanxi	18.8	13.5	3.4	11.5	9.3	56.5
Shanghai	15	15	6.1	10.9	9.3	56.3
Beijing	17.4	11.3	5	12.2	9.8	55.4
Heilongjiang	17.4	11.8	4.3	11.3	9.8	54.7
Anhui	18.6	12.8	4.8	10.7	7.6	54.5
Jilin	15.8	13.5	4.9	12.4	6.6	53.2
Liaoning	16.2	12.4	3.2	7.7	13.6	53
Shandong	15.7	10	3.8	8.4	14.7	52.7
Inner Mongolia	13.9	12.6	3.7	11.7	10.7	52.7
Henan	16.6	9.3	4.8	11.4	10.3	52.4
Jiangsu	17.8	10.2	5.3	8.9	9.8	52.1
Hebei	18.1	10.1	2.8	6.8	14.2	51.9
Tianjin	15.2	12.7	2.4	11.2	5.9	47.3
Average	20.0	13.0	5.4	11.9	9.1	59.5
Max	25.4	16.7	8.6	18.8	14.7	72.9
Min	13.9	8.3	2.4	6.8	5.1	47.3
Standard deviation	3.2	2.2	1.7	2.4	2.5	6.3

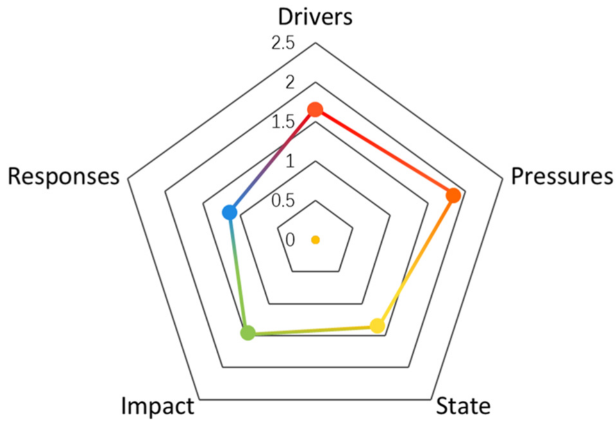

Fig. 1. Spider graph showing normalized average results for the different DPSIR categories (The average scores were normalized using Eq. (6)).

particular, the low score for responses appeals for the improvement of effective policy for groundwater sustainability. Meanwhile, there are advantages due to diversity of geology and climate in other provinces (Wang et al., 2000).

3.2. Geographical differentiation

The results garnered reveal stark differences in groundwater sustainability between southern and northern China. Most of the southern provinces including Guizhou, Guangxi, Zhejiang and Jiangxi performed better in this assessment system than the northern provinces, such as Hebei, Henan and Inner Mongolia scored poorly (Fig. 2a). However, the four southern provinces of Jiangsu, Anhui, Shanghai and Guangzhou also scored low. For drivers, the differences between northern China and southern China can be observed. Inner Mongolia had the strongest driving force to use groundwater in an unsustainable way (Fig. 2b). Following it, Shanghai, Tianjin, Shandong, Liaoning and Jilin also received relatively low scores. Pressures in the North China are also notable, with the strongest pressures in Guangdong and Xinjiang (Fig. 2c). The state of groundwater in the northern China is generally inferior to that of southern China (Fig. 2d). The three provinces of Tianjin, Ningxia and Hebei had the lowest scores, and the scores for Guangxi and Zhejiang the highest. The coastal areas are severely affected by unsustainable groundwater usage, which can be clearly seen in the lower scores received in eastern China (Fig. 2e). All provinces' that scored <10 in the category are coastal. As for responses, the provinces in eastern China have more powerful responses generally, with 32% of provinces having a score higher than 10 (Fig. 3e). To better understand the regional differences, China was divided into south China (SC) and north China (NC) according to the Qinlin-Huaihe Line (Wang et al., 1995). Fig. 3 shows the difference between subcategories.

Regional differences, which indicate the heterogeneity (Liu et al., 2007), among indicators mainly appears as two patterns. Drivers and state show the differences between northern and southern western, while pressure, impact and response exhibit the difference between western and eastern China. The difference may be caused by multiple factors of geography, climate, economy. 'State' provides an example of how these factors contribute to regional differences. Precipitation in southern China is much more abundant than it in the northern China, which means higher recharge rates and thus more abundant groundwater supply (Wang et al., 2000). However, due to the intensive agricultural and industrial activities and natural conditions, groundwater in northern China suffers from severe pollution (Gu et al., 2013; Kang et al., 2017; Wen et al., 2005). >80% of groundwater in Liaoning, Heilongjiang, Tianjin and Hebei provinces are of poor or very poor quality (MWR, 2016). Under the compounding impact of these two factors, the state of groundwater in southern China appears to be more sustainable.

3.3. Comparison and correlation of subcategories and indicators

At the national level, sustainability of different aspects is unbalanced, as seen in the in different subcategories (Fig. 4). For 'Drivers', 'Environmental Condition Change' and 'Food Production' have lower scores in this section, which means some provinces scored lower in these two subcategories. Also, the results illustrate that pressures to groundwater quality are larger than to groundwater quantity, and groundwater

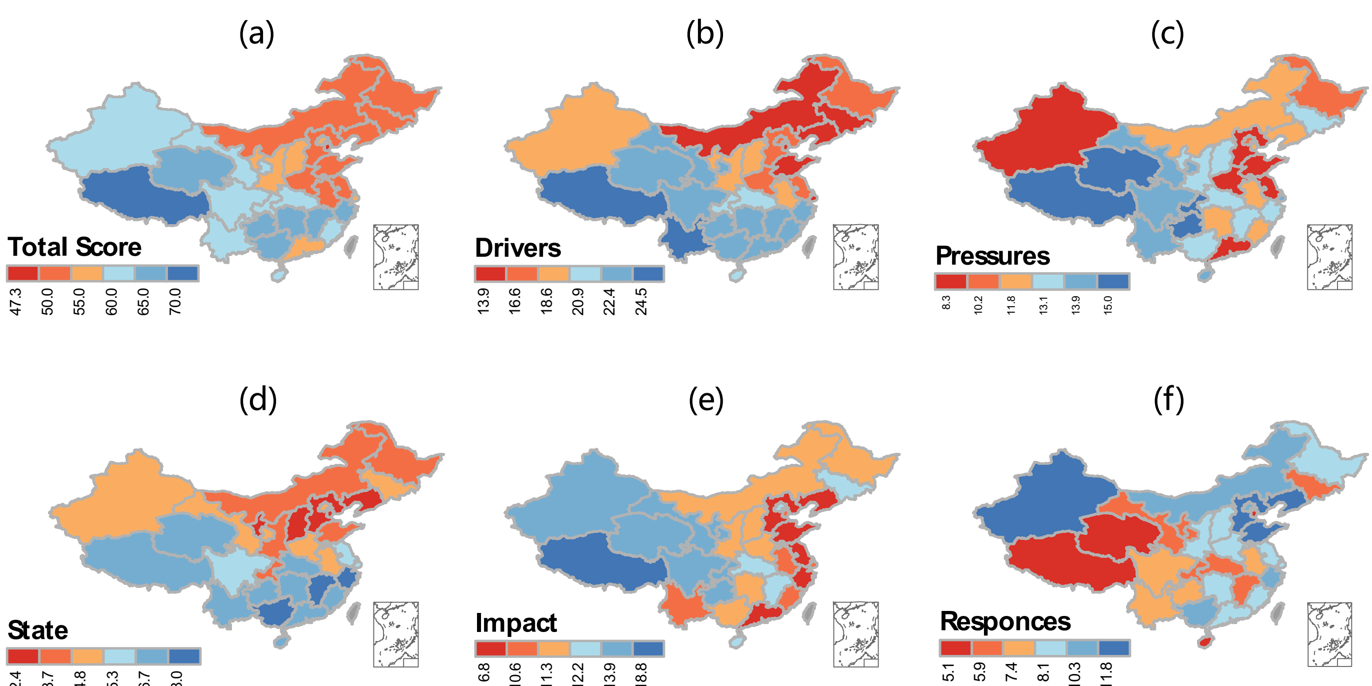

Fig. 2. Spatial distribution of overall sustainability score and scores for the five DPSIR categories Regional Differences among Categories (The data matrix of this figure is exhibited in Table 2 and was visualized using GIS).

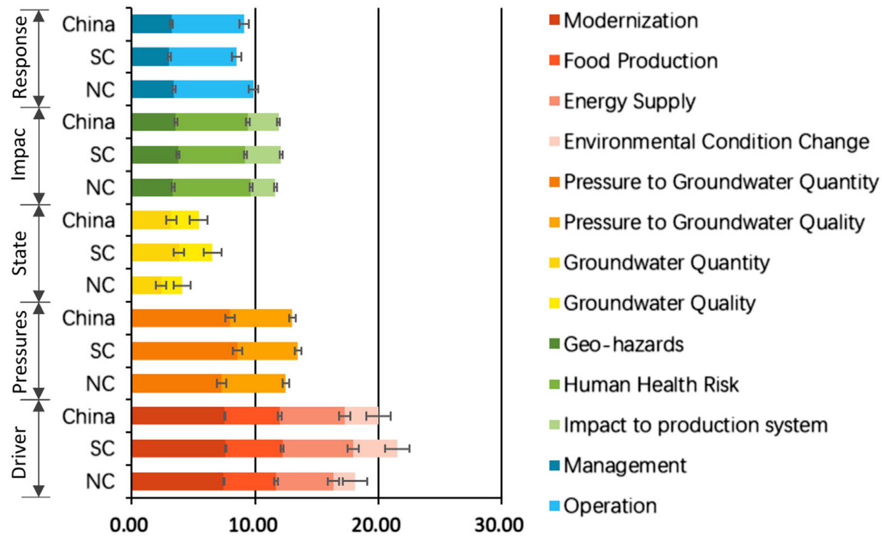

Fig. 3. Differences of Scores between all China, Northern China (NC) and Southern China (SC) among Different Subcategories (The data derived from of Eq. (5), then the score for provinces in NC, SC and China were averaged).

quality is less sustainable than groundwater quantity, due to the lower scores for 'Pressures to Groundwater Quality' and 'Groundwater Quality' in these two sections. In addition, the 'Impact to Production' get a much lower score in 'Impact' and the score for 'Operation' is slightly larger than 'Management' in 'Responses'.

Environmental Condition Change and Geo-hazards have greater variation among provinces. Due to limited data for many provinces, 'Impact to Production System' had little variation in scores. However, Tibet scored very high in this subcategory, due to low industrial impact and abundant groundwater. It is counterintuitive that modernization, a direct factor in causing unsustainable groundwater usage, scored highest in 'Divers'. Closer examination reveals that Tianjin, Shanghai and Beijing score poorly, however, most provinces and municipalities gained relatively high scores, showing the uneven pattern of development in China (Wang, 2015). 'Environmental Condition Change' and 'Geo-hazards' are widely distributed, which further proves the existence of large regional gaps. The subcategory of groundwater quality gained lower scores than groundwater quantity.

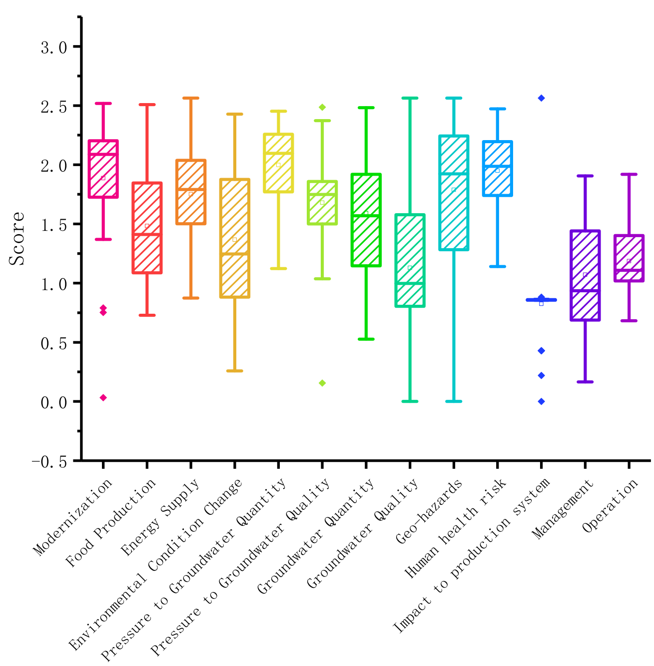

Fig. 4. Box and whisker plots for different subcategories (The data matrix is derived from Eq. (5)).

Some provinces gained a similar overall score, but different scores for various aspects. For instance, Ningxia and Guangdong scored 57.0 and 56.9, respectively, although the scores varied greatly from different subcategories and indicators. 'Pressures' in Guangdong scored the lowest, but the score for 'State' is relatively high. However, in Ningxia, the score for 'State' is the lowest in this category and the higher score for 'Pressure'. Therefore, in this assessment system, the sustainability of groundwater resources is not judged by a single aspect, but all.

The correlation coefficient between subcategories pairs was calculated, and a correlation coefficient matrix constructed, illustrating the size of correlations (Fig. 5). This gives an insight into the complex adaptive interaction and relationships among factors in the Human-Nature and groundwater system. 'Modernization' has a relatively negative correlation with 'Food Production' and 'Operation', while being positively correlated with 'Geo-hazards'. Both 'Groundwater Quantity' and 'Groundwater Quality' have strong significant positive correlation with 'Environmental Condition Change'. In addition, 'Modernization', 'Pressures to Groundwater Quantity', 'Geo-hazards' and 'Impact to production system' were negatively correlated with 'Operation'. The strongest positive correlation occurs between 'Groundwater Quantity' and 'Environmental Condition Change', with the Pearson correlation coefficient as 0.74, while the strongest negative correlation is exhibited between 'Pressure to Groundwater Quantity' and 'Operation' with the Pearson correlation coefficient as −0.62.

Interactions between components in the groundwater system and the pertaining human-nature system are manifest (Fig. 5). Therefore, groundwater and its external environment should be considered as a complex adaptive system. For instance, it is difficult to understand why 'Geo-hazards' caused by groundwater depletion, has relatively strong relationship with 'Pressure to Groundwater Quality' and 'Groundwater Quality', perhaps this is because geo-hazards are more likely to occur in places of greater development in northern China, where groundwater is often polluted by production activities (Kang et al., 2017; Li et al., 2015b; Ye et al., 2015). Seawater intrusion happens in coastal areas where water is more abundant (Shi and Jiao, 2014), consequently there is a low level of interrelationship between 'Geo-hazards' and 'Groundwater Quantity'. Therefore, geo-hazards as result of groundwater depletion also showed correlation with poor groundwater quality.

The correlations between groundwater quantity and quality subcategories are a sign that the groundwater depletion and degradation is

Fig. 5. Interrelationships of Different Subcategories (The size of the bubble indicates the Pearson correlation coefficient between two subcategories. The bigger the bubble the stronger the correlation. Blue represent negative correlation and red represent positive correlation. Mod. = Modernization; FP = Food Production; ES = Energy Supply; ECC = Environmental Condition Change; PGQn = Pressure to Groundwater Quantity; PGQa = Pressure to Groundwater Quality; GQn = Groundwater Quantity; GQa = Groundwater Quality; GH = Geo-hazards; HHR = Human Health Risk; IPS = Impact to Production System; Man. = Management; Ope. = Operation).

coupled in some provinces. In Jiangsu province, groundwater resources are abundant, but the local overexploitation has caused a geo-hazard. As much as 2.8 m land subsidence has been found in Wuxi city, and over 1 m in Suzhou city (Chen et al., 2003; Ye et al., 2015). Moreover, 67.5% of the groundwater in Jiangsu province is worse than the Class III according to the Standards of Groundwater Quality in China (MWR, 2016). Liaoning province is a coastal province in the northeast of China, with intensive heavy industrial production. There was just 7.3% of groundwater better than Class III in this area (MWR, 2016). Sea water intrusion caused by groundwater overexploitation has reached 867.8 km^2 in Dalian, further contaminating the groundwater with salinity (Zhang et al., 2014). Therefore, groundwater depletion and deterioration has occurred together and are coupled with each other.

Additionally, Poor groundwater resource sustainability becomes a driver to improve groundwater management. Both 'Operation' and 'Management' having negative relationships with 'Geo-hazard' reveals adaption to the changes imparted (Hou et al., 2012). Shandong and Hebei, which scored relatively low in groundwater sustainability, together have 17.9% of all groundwater monitoring sites in China, providing a perspective on the inter-adaptation between human and natural system.

3.4. Effect of development status

The relationship between groundwater sustainability and provincial development or production are illustrated in Fig. 6, which reveals an overall negative relationship. For instance, Tianjin with the highest GDP per capita scored lowest in groundwater sustainability. Similar patterns occur for industrial added value, thermal power generation and grain production. The industrial added value for Guangdong is 3025.9 billion RMB, which is the highest among provinces, while ranking 18 in groundwater sustainability. The greatest thermal power generation occurs in Shandong province (450.2 billion kW.h), which is ranked 26 in groundwater sustainability. As for grain production, 6324 thousand

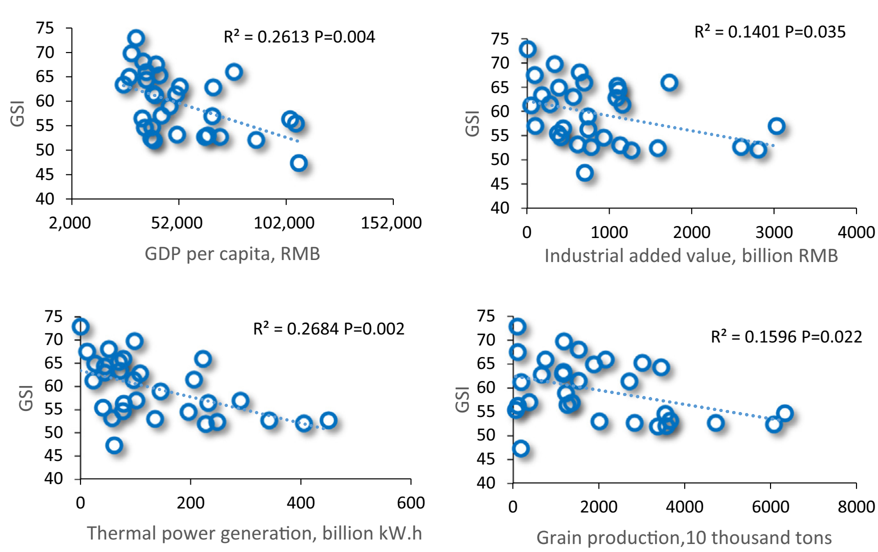

Fig. 6. Relationship between Groundwater Sustainability and Development Level.

tons of grain were produced in Heilongjiang, 10.1% of total production in China. However, Heilongjiang gained a relatively low score of 54.7, ranked at 22. Intensive industrial, energy and food production are a basis of prosperity but also a burden for the natural system. To provide adequate water for agriculture and industrial production systems, as well as sufficient drinking water supplies, groundwater is being overexploited in China. In addition, pollutants from various production activities have resulted in groundwater contamination (Hou et al., 2018b; Kang et al., 2017; Xu et al., 2008).

Interestingly, several provinces/municipalities, such as Beijing and Shanghai have high GDP per capita, but low production activities. They ranked lower than surrounding provinces, except Jiangsu and Hebei which scored worse. Therefore, the developed cities that boost their economy through technology or innovation and not production cost less in natural resources (Cao et al., 2013b). However, the cost of prosperity may be paid by other provinces. For instance, Hebei and Henan take the responsibility to provide enough food at the cost of environmental damage.

A negative correlation between groundwater sustainability and economic development and production intensity is a sign that development is damaging groundwater resources, therefore, demanding a more sustainable approach to development. Henan, a major grain-producing province in China, produced 60.671 million tons of grain in 2015 (CSY, 2016d). With limited surface water resources, irrigation in Henan relied on groundwater exploitation, with over a million irrigation wells (Chen and Ma, 2017). However, the rate of water-saving irrigation only reached 20.6%, which reveals the unsustainable nature of food production in Henan (CSY, 2016b). When sustainable approaches are selected, the conflict between intensive production activities and groundwater sustainability will be reduced. Furthermore, the negative correlation is also a profound warning for the less developed provinces of China, such as Qinghai, to develop with a more sustainable plan in the future.

3.5. Policy implications

Comparing scores of different subcategories provides us guidance to improve overall sustainability of groundwater. For example, to avoid groundwater resource pollution by increasingly intensive human activities, policies for protecting groundwater need to be established. Zhejiang, with a poor impact score, especially for geo-hazards, would be advised to take more measures to prevent overexploitation of groundwater to alleviate the threat of land subsidence and sea water intrusion (Li et al., 2015a; SOA, 2015). For the most of arid and semi-arid areas in China, such as Hebei, effective responses have occurred for the terrible groundwater situation and coupled unsustainable impacts, which should be implemented continuously. However, provinces such as Tianjin, with weak responses, should take more measures to support groundwater sustainable management.

The coupled depletion and deterioration of groundwater is calling the management of groundwater quantity and quality to be promoted simultaneously. Apart from anthropic and natural impact, the groundwater level falling appeared to be a driver to groundwater degradation, through seawater intrusion in coastal area and the leakage recharge of saline water in inland area (Liu et al., 2009; Shi and Jiao, 2014). Groundwater unsustainability in China appeared to be a coupling issue in both dimension of quantity and quality. Consequently, the management of groundwater in quantity and quality can be considered and implement together. Moreover, measures such as the limit of groundwater overexploitation in coastal area may simultaneously prevent groundwater from depletion and degradation.

Regional groundwater sustainability should be understored. The geographical distribution of scores for groundwater sustainability reveals not only the geographical differences but also the regional homogeneity. For instance, the provinces included in the North China such as Beijing, Hebei, Tianjin, are close to each other, with generally similar natural condition and development characteristic. To support the rapid development of Beijing, Hebei and Tianjin have shouldered tremendous pressures. The poor performance of groundwater sustainability in northern China is a response to intensive human activities (Foster et al., 2004). To address this, a more sustainable development in this region plans in the dimension of economic and society is required. Moreover, it is not the development causing the groundwater unsustainability, but the unsustainable development style and method, which should also be underscored and improved in the future.

More adaptive management and governance of groundwater resources should be carried out. Awareness of interactions in complex system may help adaptation to the local situation. Groundwater systems are interrelated with multiple factors in the human-nature system. Groundwater policies should be responsive (Megdal, 2018). For instance, when groundwater depletion occurs, alternative water sources should be utilized instead of allowing overexploitation that causes irreversible damage to nature systems. Continuously changing climate also underscores the importance of adaptive management of groundwater resources (Megdal, 2018). Droughts and floods are increasingly suffered (Long et al., 2014). Thus, it is critical to set up sustainable groundwater management which will be adaptive and resilient to increasingly tough climatic conditions (Megdal, 2018). In addition, it is vital to link groundwater resource management with food production, energy generation, land use and the environment, according to the interrelationships between them (Bazilian et al., 2011; Megdal, 2018; Ringler et al., 2013). Local factors should be considered in the management and governance of groundwater. For example, in southwestern China, a karst area with little soil protection, pollutants can enter the groundwater more directly and easily (Nguyet and Goldscheider, 2006). Accordingly, appropriate measures for preventing groundwater deterioration and sustainable remediation in this scenario should be taken (Hou et al., 2012; O'Connor et al., 2018; Song et al., 2018).

In addition, the indicators assessed in this framework provide a comprehensive analysis on groundwater human-nature systems. Long-term monitoring for the different kinds of indicators of groundwater should be set up and modified to help us better explore the complex systems and provide robust support for policy and decision making (Wang et al., 2019; Zhang et al., 2019).

3.6. Sensitivity analysis

The component weighting is a critical factor of the model on the final results. In this study, we gave the same weighting to each indicator. In the model presented, the weighting of each indicator was equal, so that the weighting of each category varied by the number of indicators applied (WS1). For the sensitivity analysis, a weighting scheme that applied equal weighting to each category is conducted, so that the weight of each indicator varied (WS2). The sensitivity of overall results to the different weightings are shown in Fig. 7.

By using WS2, the weighting for 'Drivers' decreased from 2.56 to 1.67, weighting for 'Pressures' increased 2.86, weighting for 'State' increased to 5.00, and weighting for 'Impact' and 'Responses' is 2.50. The total GSI of China reduced slightly from 59.5 to 58.6. The scores for 'Drivers' and 'State' changed the most, reducing from 20.0 to 13.0 and increasing from 5.4 to 10.6, respectively. The GSIs for each province also varied. The GSI for provinces such as Tibet, Guizhou, Sichuan, Gansu, Shaanxi, Ningxia, Hebei and Tianjin increased, while for provinces such as Shanghai, Jiangxi, Guangxi, Qinghai and Hainan it decreased. GSI in Ningxia increased most (by 3.4) while in Shanghai it decreased the most (by 1.8). The rank of Liaoning rose most, from 29 to 25, and the rank for Shanghai dropped the most, from 16 to 21. The changes in GSI were mainly due to the weighting change of 'Drivers' and 'State' categories.

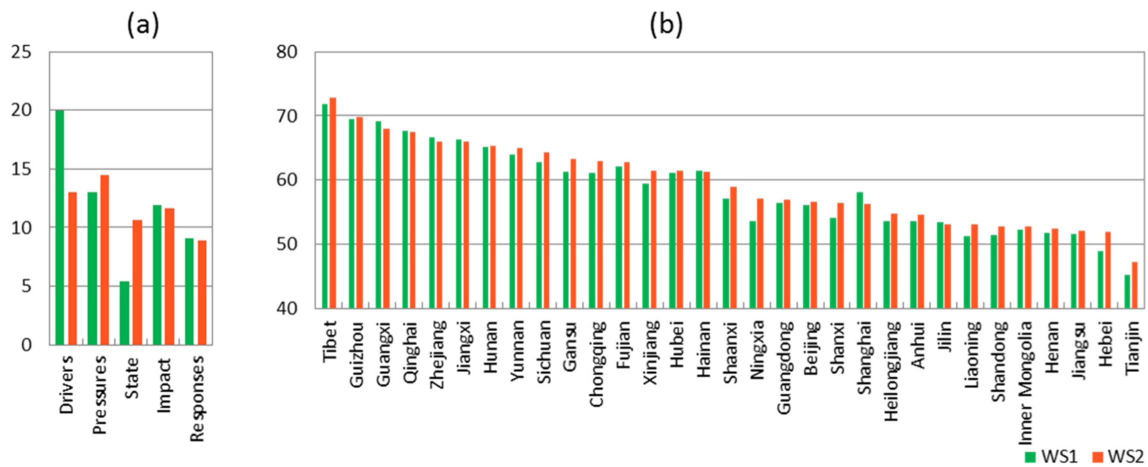

Fig. 7. Sensitivity analysis for weighting scheme. (WS1: previous weighting scheme (same weighing for each indicator), WS2: same weighting for each category, (a) scores for different categories and data matrix derived from Eq. (5), (b) GSI for different provinces and data matrix derived from Eq. (4)).

4. Conclusions

The challenges confronting China in maintaining its sustainable groundwater resources are immense, with groundwater depletion and deterioration being threats to sustainable development. Moreover, groundwater is a key factor in the coupled human-nature system. Therefore, the first comprehensive groundwater sustainability assessment framework for national-scale assessment based on DPSIR was developed that including the dimensions of society, economy and environment. The DPSIR indicators were chosen to reveal not only the situation of groundwater sustainability in China, but also the interaction between groundwater and human-nature systems. The indicator system was divided into the five DPSIR categories, which we further divided into 14 subcategories. The framework presented was established on the existing theories of the interaction between groundwater and coupled human-nature systems, as well as other previous research on GSA.

The model was used to conduct the first national groundwater sustainability assessment for mainland China, including scores derived for the different provinces and municipalities. An evaluation of the groundwater resource sustainability of 31 provinces revealed that Tibet scored the highest and Tianjin the lowest. Significant regional differences were identified. In specific, groundwater in southern China is considered more sustainable than that in northern China. A correlation between subcategories of groundwater quality and quantity reveals the coupling of groundwater depletion and deterioration in China.

A negative relationship between groundwater sustainability and development levels was explored, which indicates the need for a more sustainable development in China. Comparing scores of different subcategories provides us with guidance to improve the overall sustainability of groundwater resources. For example, to avoid groundwater resource pollution by increasingly intensive human activities, policies for protecting groundwater need to be established. The GSA framework provides overall guidance for different provinces to promote groundwater sustainability for different aspects. More adaptive management and governance of groundwater resources should be carried out. Awareness of interactions in complex system may help adaptation to the local situation. To cope with changing climate and increasing demand on groundwater resources, adaptive long-term management is recommended.

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